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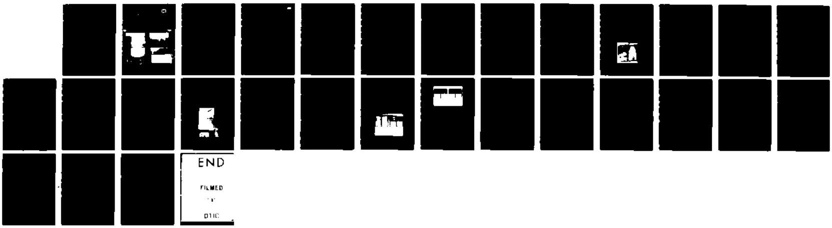

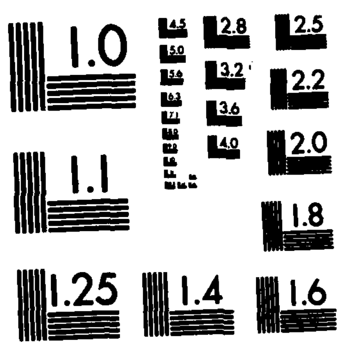

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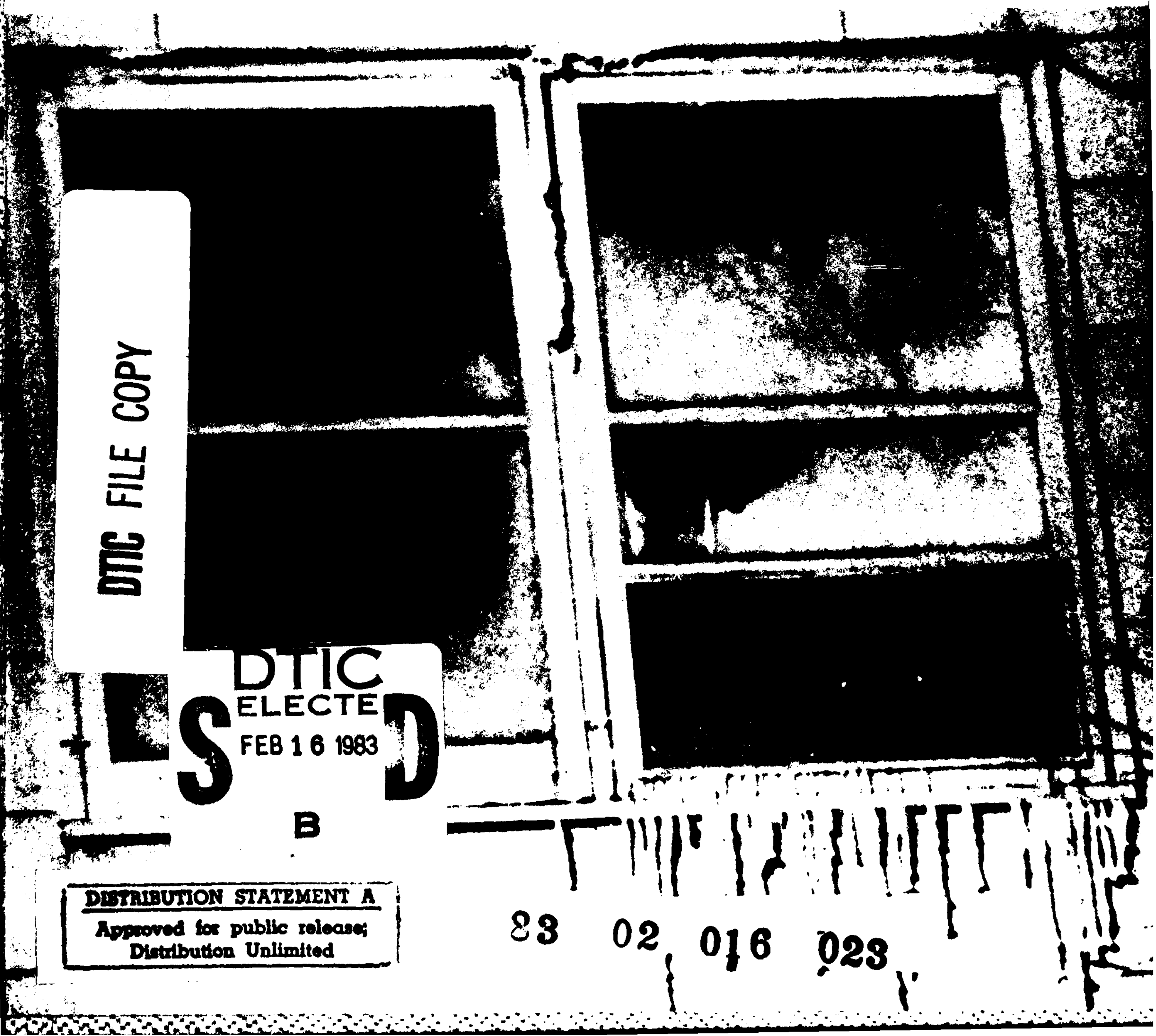
Window performance in extreme cold



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Cover: Tight storm sash detaining moisture escaping from the building and causing icing problems.

CRREL Report 82-38

December 1982

Window performance in extreme cold

S.N. Flanders, J.S. Buska and S.A. Barrett

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Extreme cold causes heavy buildup of frost, ice and condensation on many windows. It also increases the incentive for improving the airtightness of windows against heat loss. Our study shows that tightening specifications for Alaskan windows to permit only 30% of the air leakage allowed by current American airtightness standards is economically attractive. We also recommend triple glazing in much of Alaska to avoid window icing in homes and barracks. We base our conclusions on a two-year field study of Alaskan military bases that included recording humidity and temperature data, observing moisture accumulation on windows and measuring airtightness with a fan pressurization device.

PREFACE

This report was prepared by S.N. Flanders, Research Civil Engineer, of the Civil Engineering Research Branch, Experimental Engineering Division, and J.S. Buska, Research Hydraulic Engineer, and S.A. Barrett, Geophysicist, of the Alaskan Projects Office, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this research was provided by DA Project 4A762730AT42, *Design, Construction and Operations Technology in Cold Regions,* Task C, *Cold Regions Operation and Maintenance of Fixed Facilities,* Work Unit 010, *Improving the Thermal Performance of Military Facilities.*

The authors are grateful for the efforts of their colleagues, Wayne Tobiasson and Alan Greatorex, in providing advice, resources and the original impetus for this project. They also thank Tobiasson and G. Phetteplace for technically reviewing the manuscript of this report.

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NOMENCLATURE

Window terms

Sash—movable/removable frame holding the glass of a window.

Double-hung window—window with a single pair of vertically sliding sashes.

Double double-hung window—window with two parallel pairs of vertically sliding sashes.

Double-sash vs single-sash windows—windows with two vs one layer of sashes, e.g. a double double-hung window is in the double-sash category.

Triple glazing—three layers of glass, separated by air spaces, through the thickness of the window.

Double-sliding windows—windows with a pair of horizontally sliding sashes.

Casement windows—windows with sashes hinged on the side.

Symbols

C	airtightness coefficient
E	exposure coefficient
h	vertical distance of an air leakage site from the neutral plane in a building
H_A	annual heat loss
n	flow exponent
N_i	number of days in month i
P_c	pressure across window due to stack effect
P_w	pressure across window due to wind
Q	rate of flow, air leakage
S	savings in Btu/season-foot of crack
T_D	indoor dewpoint temperature
T_I	indoor ambient temperature
T_s	temperature of the indoor window surface
T_i	indoor temperature (°R) at time t
T_o	outdoor temperature (°R) at time t
V	wind velocity
ΔP	pressure difference across a crack
ΔT_{ID}	difference between the indoor ambient and indoor dewpoint temperatures
ΔT_{IO}	difference between the indoor and outdoor ambient temperatures
ΔT_{IS}	difference between the indoor ambient temperature and the temperature of the indoor window surface

CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
foot	0.3048*	meter
$foot^2$	0.09290304*	$meter^2$
$foot^3$/minute	0.0004719474	$meter^3$/minute
inch of water (60°F)	248.84	pascal
gallon	3.785412	liter
mile/hour	1.609344*	kilometer/hour
pound-force/$inch^2$	6.894757	kilopascal
British thermal unit	0.0546802	kilojoule
°F hr ft^3/Btu	0.1761102	kelvin $meter^2$/watt
degrees Fahrenheit	$(t_{°F} - 32)/1.8$	degrees Celsius
degrees Rankine	$t_{°R}/1.8$	kelvins

*Exact

WINDOW PERFORMANCE IN EXTREME COLD

S.N. Flanders, J.S. Buska and S.A. Barrett

INTRODUCTION

Window design for extreme cold warrants special attention because heat loss during the window's lifetime can cost many times the price of the window itself. A window adequate for moderate winter weather can fail to perform satisfactorily in extreme cold. In Alaska many windows sustain severe accumulations of frost, ice and moisture (Fig. 1) which obscure vision, prevent the operation of sashes and damage buildings.

This report is about heat loss caused by window air leakage and how to avoid moisture problems. We recommend that windows in Alaska be much more airtight than required by current American window industry and Corps of Engineers standards. Furthermore, windows should retain a high level of airtightness after installation.

We further recommend triple glazing for much of Alaska. This makes economic sense in many places and is an important way to avoid moisture buildup on windows in residential buildings, especially where

Figure 1. Heavy accumulations of frost that can lead to sashes frozen shut and meltwater damage on interior finish. An open storm sash (left) negates the value of having two sets of sashes.

high humidities and the use of curtains or shades are common.

These recommendations result from two years of winter observations, measurements and analysis of windows at three military bases in central Alaska. A portable airtightness measurement device gave us performance characteristics for a large range of air pressure differences across the window thickness. Measurements of the temperature and humidity inside Alaskan buildings gave us indoor dewpoint temperatures over the heating season.

PREVIOUS WORK IN COLD WEATHER WINDOW PERFORMANCE

The literature about windows for use in extreme cold is quite sparse. Rice (1975), in one of the few references on this subject, mentions the danger of heavy frost accumulation on windows and recommends having the innermost sash be the most effective vapor-retarding layer. The inner sash should limit the flow of indoor humid air to a sufficiently low level to prevent icing. Another method of preventing ice buildup would possibly be maintaining an air stream across the window.

Beckett and Godfrey (1974) published a condensation prediction chart, a nomogram with variables of inside and outside air temperatures, relative humidity and thermal transmittance. However, they did not report the moisture loads that result from various building uses.

Paliwoda (1978) discusses the extreme variation of window utility during the changes of seasons in the Far North. In winter when daylight is brief, the utility of windows is much less than in temperate climates. In summer, darkness is brief and daylight becomes a nuisance during sleeping hours. Paliwoda recommends a system of insulating shutters that vary the size of the window according to season and thereby balance window utility with thermal liability throughout the year.

Reference literature on windows available to designers and specifiers shows little appreciation of the severe effects on windows caused by the Far Northern winter climate. ASHRAE (1977) has useful data about air film resistance, airtightness and insulation, but it does not deal adequately with controlling frost or condensation on windows.

ASHRAE (1977) gives current industry standards for window airtightness and explains how to calculate infiltration and heat loss due to infiltration. Both ASHRAE and Jennings (197[illegible]) give air le[illegible] figures for a variety of windows and do[illegible]. T[illegible]r data for older double-hung windows suggest that the installed performance of weather-stripped windows meets or exceeds the industry standards for airtightness. This is contrary to our experience and that of Weidt et al. (1981).

Weidt et al. (1981) measured the air leakage between the sash and the frame of installed windows in Minnesota with a fan pressurization device. They found that random samples of windows from factory assembly lines typically satisfied the industry standard of 0.5 ft^3/min per ft of crack for a pressure difference of 0.2 in. of H_2O, but installed windows seldom did. Installed casement windows (at 0.23 ft^3/min ft) were the only type of window with airtightness better than the standard, whereas most types had values in excess of 0.6 ft^3/min ft. The manufacturer of the window was often a good indicator of airtightness. Material (aluminum vs wood) and whether the installation instructions were followed had relatively little influence on airtightness of the window units themselves. Typical construction defects were weather stripping discontinuity and poor sash fit, resulting in leakage at corners, sills and meeting rails.

Hastings and Crenshaw (1977) touched on all the major considerations for lowering energy consumption due to windows. The authors updated Lund and Peterson's 1952 study to show fuel cost savings for a double-hung window ranging between \$36 per year in Washington, D.C., to \$78 per year in North Dakota attributable to installing all-metal weatherstripping.

Kusuda and Collins (1978) simulated "the effects of window size, heat transfer, solar shading and compass orientation for typical commercial and residential modules located in a climate typical of Washington, D.C." They demonstrated that increased window size, combined with covering the windows at appropriate times, setting back the thermostat at night and avoiding a northerly orientation, can result in a net energy savings in that climate.

While ASHRAE (1977) listed the American National Standards Institute (ANSI) maximum permissible air leakage rates (depicted as a point marked "COE standard" in Fig. 2), the Norwegians have stricter classifications, as described in Beckett and Godfrey (1974) and also shown in Figure 2. The American 0.5 ft^3/min ft of crack standard is borderline between their two leakiest categories.

Based on this review of the pertinent literature we chose to limit our investigation to airtightness and the control of frost and condensation. These topics have a significantly different impact in severe cold than in the more temperate areas dealt with in the literature.

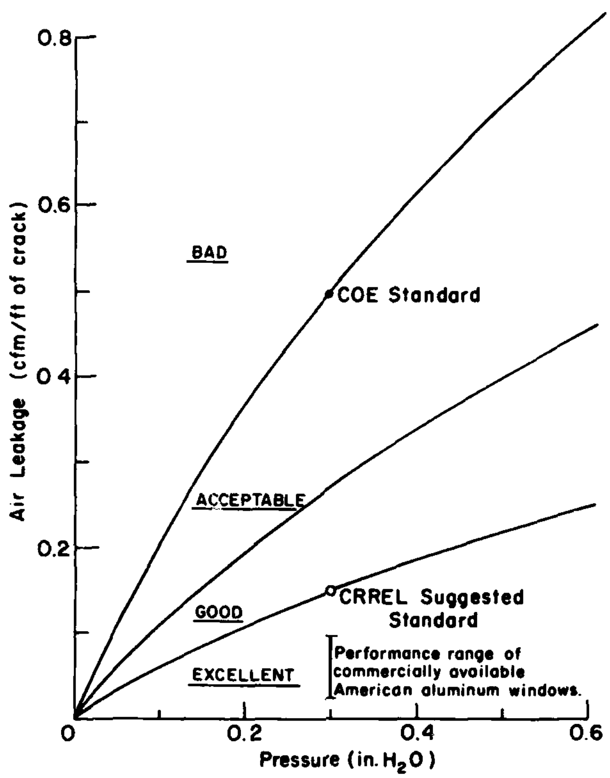


Figure 2. How American windows compare with the four airtightness categories from Norwegian standards (graph by A. Greatorex, CRREL). (A test pressure of 0.3 in. H_2O is the basis for American standards.)

INVESTIGATION

Our work concentrated on military buildings in Alaska that have undergone an extensive window replacement program in recent years, thereby indicating which window design improvements intended for extreme cold are worthwhile.

Data acquisition and analysis

Our work covered three principal research efforts: 1) characterization of moisture-temperature loads causing condensation and icing on windows, 2) observation of the susceptibility of different window types to icing and condensation, and 3) determination of the airtightness of windows designed for extreme cold.

We made icing and condensation observations over the temperature spectrum shown in Table 1. Likewise, we tested aluminum and wooden double-sash and wooden single-sash windows for airtightness at outdoor temperatures ranging between -40° and 20°F as shown in Table 2. We made these observations in four office locations, seven barracks rooms and 14 family housing units at Fort Wainwright, Eielson Air Force Base, and Fort Greely.

Hygrothermographs placed at 15 locations in offices, barracks and family quarters gave us temperature and humidity data for each type of use. In addition, we took sling hygrometer readings and hourly weather data with outdoor temperatures for each military base. We observed the conditions that caused moisture and ice to accumulate on windows and compared these observations with a simple thermal model. In general, the model was a good predictor of when moisture or ice would occur on a window pane.

Table 1. Distribution of frost and condensation observations.

Number of panes	Sash material	Number of locations	Number of moisture observations at temperatures (°F) down to and including: -40°	-30°	-20°	-10°	0°	10°	20°	Total
Three	Aluminum	8	3	12	2	4	2	3	5	31
	Wood	7								
Two	Aluminum	3	3	8	2	1	1	2	4	21
	Wood	7								
Totals		25	6	20	4	5	3	5	9	52

Table 2. Distribution of airtightness measurements.

Sash system	Number of locations	Number of airtightness measurements at temperatures (°F) down to and including: -40°	-30°	-20°	-10°	0°	10°	20°	Totals
Aluminum double	6	1	2	1	-	1	2	3	10
Wood double	4	-	-	-	-	-	2	3	5
Wood single	5	-	1	-	-	-	1	3	5
Totals	15	1	3	1	0	1	5	9	20

Modeling the window thermal regime

The purpose of our model was to predict when a window will accumulate frost or condensation. As dry bulb temperature falls, relative humidity (RH) increases. When the air can hold no more moisture (RH = 100%) it has reached its dew point, and condensation or frost occurs. The difference between the indoor dry bulb temperature T_I and the dewpoint T_D we call ΔT_{ID}. This difference indicates how much lower the inside surface temperature of the window T_S must be than the indoor temperature to accumulate moisture. ΔT_{IS} indicates the difference of $T_I - T_S$.

We use ΔT_{ID} and ΔT_{IS} because they offer mutual comparison without reference to a specific indoor temperature. When $\Delta T_{IS} > \Delta T_{ID}$ the window will accumulate frost or condensation.

The temperature gradient across the thickness of the window and its air films is a function of indoor and outdoor ambient temperatures and the thermal properties of the layers, as shown in Figure 3. Thus, the temperature spread between the indoor ambient and the indoor surface of a window is a function of the window's thermal characteristics and of the temperature spread between indoors and outdoors ΔT_{IO}:

$$\Delta T_{IS} = \frac{R_1}{\Sigma R} \Delta T_{IO} \qquad (1)$$

where

R_1 = thermal resistance of the indoor air films adjacent to indoor glass surface (°F hr ft²/BTU), 0.61 (no curtain) or 1.61 (with curtain)

ΣR = thermal resistance of entire window system (°F hr ft²/BTU) consisting of some or all of the following values:

Outside air film: 0.17
Air between panes 1 and 2: 1.0
Air between panes 2 and 3: 0.75
Air between inner pane and curtain: 1.0
Indoor air film: 0.61 (source: ASHRAE [1977]).

The borderline ΔT_{IS} for surface temperature to reach the dewpoint is shown in Figure 4 as a straight line function of ΔT_{IO} as ΔT_{IO} increases. This plot shows that the surface of the window becomes cooler, and therefore the greater the spread between indoor ambient and surface temperature ΔT_{IS}. When ΔT_{IS} is greater than the spread between indoor ambient and dewpoint temperatures ΔT_{ID}, we expect condensation or icing on the window.

Indoor dew point and window surface temperatures combine to cause frost or condensation of moist air.

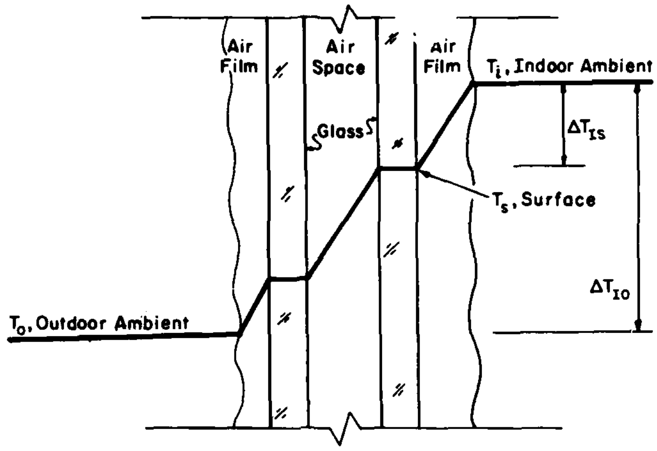


Figure 3. Approximate temperature gradient across a two-pane window. ΔT_{IS} in Figure 4 equals $T_I - T_s$

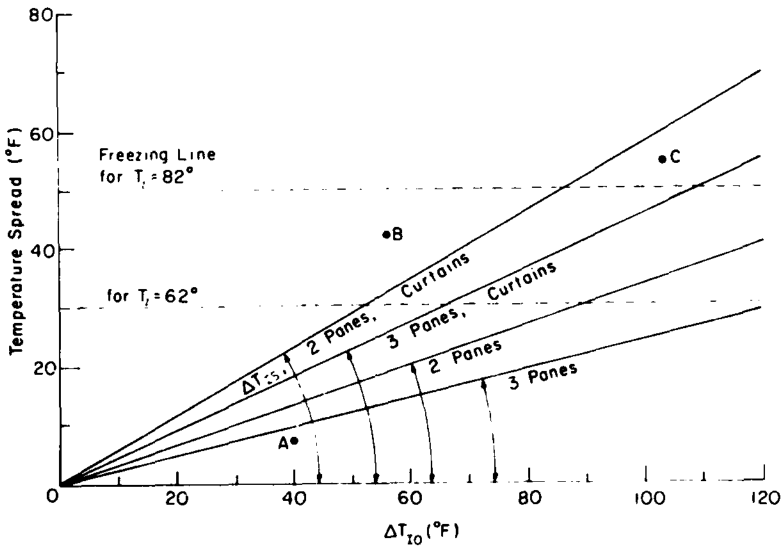
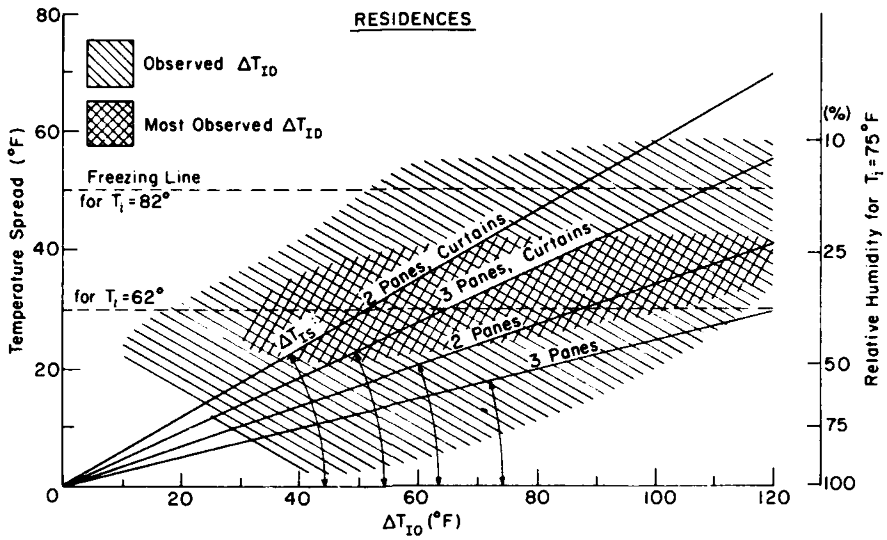


Figure 4. Lines of ΔT_{IS} for different window configurations. One should expect condensation on the indoor pane for $\Delta T_{ID} < \Delta T_{IS}$ and further expect frost for values of $\Delta T_{IS} > T_I - 32°F$. The area above each line is the "safe" area for that configuration. Point A would have moisture accumulation for all four window configurations. Point B would have no accumulation. Likewise, point C would not accumulate moisture except for a double-glazed window with curtains, in which case frost would occur even with an indoor temperature of 82°F.



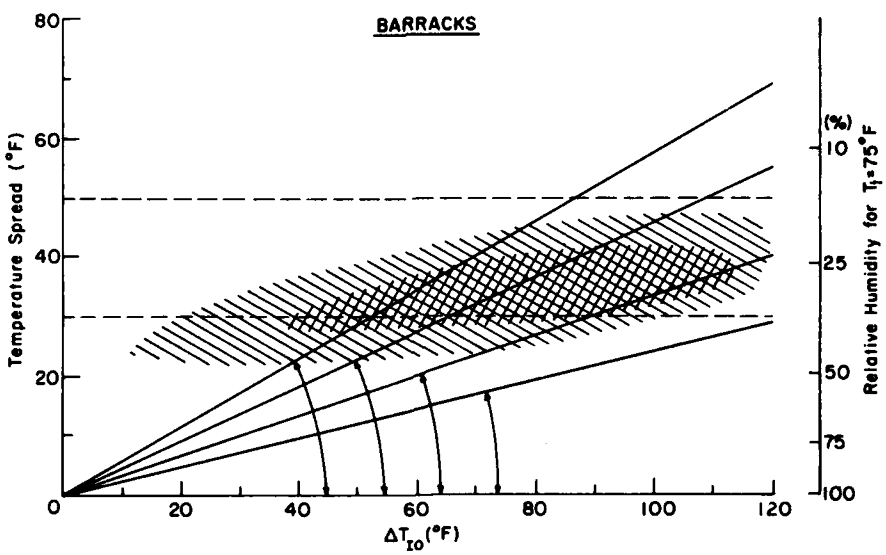


Figure 5. Likelihood of frost or condensation according to building use. This figure superimposes measured ΔT_{ID} on the model from Figure 4 for three building uses. One should expect condensation below the sloped lines and frost when $\Delta T_{IS} > T_I - 32°F$. Appendix B shows data for offices and demonstrates how "observed" and "most observed" categories were determined. Appendix C shows sample data for observations of icing.

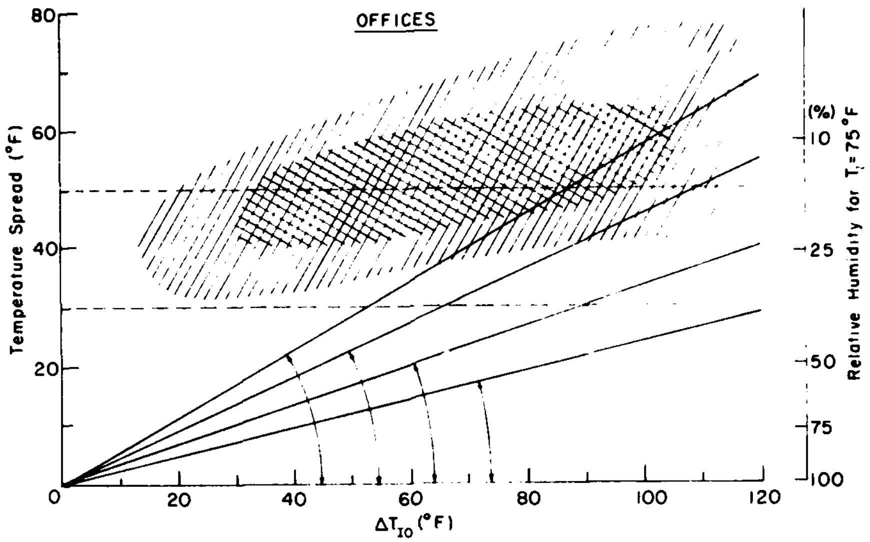


Figure 5 (Cont'd).

Since ΔT_{IO} affects both window dew point and surface temperatures, we plotted data from indoor hygrothermograph measurements and outdoor temperature records, showing ΔT_{ID} and ΔT_{IS} as a function of ΔT_{IO}. Figure 5 superimposes the ranges of moisture loads measured in barracks, family housing and office spaces on the thermal model of Figure 4. Family housing was the moistest and office spaces the driest.

Figure 5 indicates when moisture or ice will form for each of the four window configurations. We would seldom expect ice or condensation on a triple-glazed window without curtains, but these moisture problems would be more frequent in residences on such windows with drapes, especially as ΔT_{ID} increases. A double-glazed window without curtains probably won't suffer moisture problems in an office. However, in a residence, moisture and ice problems are not only likely, but guaranteed, if curtains cover the window as we observed in many instances.

Moisture and ice observations

Moisture and ice accumulation on windows has four primary causes: 1) cold indoor glass, 2) highly conductive frames or sashes, 3) air leakage that cools sashes or frames, and 4) vapor-loose indoor sashes and vapor-tight exterior sashes that permit vapor migration past the inner pane. Refreezing of meltwater migrating from a thawed area on the window is a secondary mechanism.

Cold indoor glass drew our main attention, because most manufacturers succeed in making the frame and sash less conductive than the glazing system. Furthermore, if our recommendations regarding airtightness are followed, then air and vapor migration should not be a source of moisture around sashes. However, without guidance on the number of glazings, someone might easily choose a well-designed unit with too few panes.

Our window observation technique included looking for frost and condensation on the frame, sash and glass; this was recorded on a form and on film. At the same time we recorded dry and wet bulb indoor temperatures and outdoor temperature. We compared our expectations for moisture and ice accumulation on windows with our observations. According to the window model (Fig. 5), we would expect moisture accumulation if ΔT_{ID} from the moisture data determines a point below the ΔT_{IS} borderline for the window's configuration of panes and covering. If, at the same time, that point represents a ΔT_{ID} above the difference between 32°F and room temperature, we expect frost or ice, as Figure 5 illustrates for indoor temperatures of 62° and 82°F.

The thermal model and the example in Figure 4 represent steady-state conditions. Since our observations were made during the daytime, it was often likely that ΔT_{IO} at the time of observation would not predict the moisture or ice we observed because any accumulation that occurred at night—during maximum ΔT_{IO}—would be diminishing. Direct exposure to sunshine or to radiators adds factors that could decrease the model's accuracy. Appendix C presents sample icing data.

Airtightness testing and analysis

We tested airtightness with the pressurization device shown in Figure 6. It pressurizes the plastic covering sealed around the window with a known rate of flow at a known pressure drop across the window. Increasing pressure with a given airtightness results in flow increases according to curvilinear relationships similar to those depicted in Figure 2 and described by the equation

$$Q = C\,(\Delta P)^n \qquad (2)$$

where

Q = rate of flow, air leakage
C = airtightness coefficient
ΔP = pressure difference across the crack
n = flow exponent.

In this report we distinguish between airtightness C, a quality of the construction, and air leakage Q a rate of flow depending on airtightness and the circumstances causing an air pressure drop across the construction.

The recommended procedure for use of the pressurization device is to perform both positive and negative pressure tests. In the calculations a flow exponent, n = 0.7, is recommended by the manufacturer of the testing device. We found this value to fit the data well.

Our procedure was to apply the pressurization device to the window frame to test the airtightness of the sashes from the indoors. We tested windows with multiple sets of sashes with both sets closed and with one set open at a time. In addition, we sealed the device to the window's rough opening to test the airtightness of the complete system. However, this test risks forcing air through the adjacent wall and back to the same side of the construction as the testing apparatus and therefore not measuring leakage to the other side.

Figure 6. Fan pressurization testing for airtightness. The sealed-off window passes a known flow rate through its cracks at a known pressure difference across the window.

In our analysis we lo^ked at the total flow of air through the window at a given pressure difference. Given the number of linear feet of crack in the window system, we obtained its airtightness in terms of cubic feet per minute per foot of crack at 0.3 in. of water. Appendix A discusses how hygrothermograph and temperature data may offer another means of assessing building airtightness.

ANNUAL HEAT LOSS FROM AIR LEAKAGE

A designer can base life cycle cost (LCC) analyses of insulation thickness on heating degree-days to determine how the cost of adding insulation saves on the cost of fuel over the economic lifetime of the building. However, no climatological basis equivalent to heating degree-days has been established to evaluate the effects of tightening windows (or any other construction element in a passively ventilated building) against seasonal heat loss from air leakage.

The equation we use to express annual heat loss due to air leakage is quite complicated. We approximate this with

$$H_A = \int_{\text{Sep}}^{\text{May}} 26\, C[P_w + P_c]^n (T_i - T_o)\, dt \quad (3)$$

where

H_A = annual heat loss (BTU/season-ft of crack)
P_w = pressure across the window due to wind (in. of H_2O)
P_c = pressure across the window due to stack effect (in. of H_2O)
T_o = outdoor temperature (°R) at time t (hr)
T_i = indoor temperature (°R) at time t (hr).

The constant, 26, is simply derived from (24 hr/day) (0.018 Btu/ft^3 °R) (60 min/hr), where 0.018 Btu/ft^3 °R represents the assumed heat capacity of air. Unfortunately, it is difficult to separate the heating load due to the environment, $(T_i - T_o)$ in eq 3, from that due to the thermal characteristics of the building which also vary with temperature.

Equation 3 is, in part, an expansion of eq 2. Its components are derived from ASHRAE (1977). Pressures across the window (ΔP) from wind and stack effects are the driving causes for air leakage. For wind pressure

$$P_w = E\,(4.82 \times 10^{-4})\, V^2 \quad (4)$$

where P_w is the pressure differential attributable to wind (in. of water), E the exposure coefficient (according to ASHRAE [1977] we used 0.575), and V the wind velocity (mph).

Wind velocity independently adds to, or offsets, the potential for air leakage due to the stack effect, depending on wind direction and the location and size of openings in the building. The squared term for wind velocity in eq 4 makes strong winds much more significant than mild winds.

Stack pressure affects air leakage, with warm air escaping from the top of the building and being replaced with denser, cold air entering at the bottom. The air flow through each crack depends on the distance of that crack from the neutral plane (the plane where a crack would have no net leakage due to stack effect), which in turn depends on the location and size of all cracks in the structure.

For calculating the effect of stack pressure, we assumed a 14.7-psi air pressure and used two building heights with the neutral plane at midheight. For a one-story building we assumed the "typical" segment of crack to be 1.4 ft from the neutral plane and 5.5 ft from the neutral plane in a two-story building. In both cases we assumed that the wind was reinforcing the effect of stack pressure. Then from ASHRAE (1977),

$$P_c = 0.52\,(14.7)\, h\,(1/T_o - 1/T_i) \quad (5)$$

where P_c is the pressure differential attributable to stack pressure (in. of H_2O), h the vertical distance of the crack segment away from the neutral plane (ft), and T_o and T_i the outdoor and indoor temperatures (°R), respectively.

According to ASHRAE (1977) heat loss (Btu/hr) is again proportional to Q from eq 1, with $\Delta P = (P_w + P_c)$ and $\Delta T_{IO} = (T_i - T_o)$:

$$H = 0.018\,(60)\, Q\, \Delta T_{IO}\,. \quad (6)$$

To compute the energy savings between two airtightness options, 1) 0.5 ft^3/min ft and 2) 0.15 ft^3/min ft, over a heating season, we combine these variables to give

$$\Sigma S = \sum_{i=\text{Sep}}^{\text{May}} (24\ \text{hr/day})(N_i\ \text{days/mo})\,(H_1 - H_2) \quad (7)$$

where

ΣS = sum of the savings in Btu/season-foot of crack
N_i = number of days in month i
ΔT_{IO} = difference between indoor and outdoor ambient temperatures (°F or °R)

$(H_1 - H_2)$ = difference in heat losses due to stack and wind pressures between options 1 and 2, calculating each H with eq 6.

In order to approximate the annual savings for tightening cracks in window construction, we employed eq 7 with windspeed and outdoor temperatures set at their monthly averages. The use of average windspeed creates a low cumulative pressure due to wind because the V^2 term would cause windspeeds reading above the mean to have higher values over the month than those below the mean. We have insufficient knowledge of the correspondence between temperature and wind speed; however, the coldest periods tend not to be the windiest. For the range of temperatures between -40° and 80°F, the expression for pressure due to stack effect is close to linear. The flow exponent n in eq 1 reflects crack size. For our calculations, we used $n = 0.65$, as recommended in ASHRAE (1977).

In our analysis of heat loss due to air leakage, we ignore latent heat. However, this can be a significant additional incentive for improving airtightness, depending on the amount of moisture generated within a space. The more moisture generated by cooking, bathing, humidifiers, etc., in liquid form, the more energy is consumed in evaporating this moisture during the course of maintaining a set indoor temperature.

Given the energy savings calculated in eq 7, we can compute its dollar worth by using present worth factors based on a 25-year economic life for the window, a 10% time value of money and escalation rates over and above the prevailing inflation rate of 5% for coal and 8% for natural gas and heating oil. Considering such factors as heating plant efficiency (75%) and the heat available from occupancy (16% of the total required), we offer the following present worth values for fuel costs in dollars per 10^4 Btu:

Ft. Wainwright (1979) 0.43

Fairbanks 1.6 (at $1.00/gal. heating oil)

Ft. Richardson (1979) 0.31

Anchorage 0.39 (at $0.19/100 ft^3 natural gas).

The justification for these values is discussed more thoroughly in Flanders and Coutts (1982). We calculated the present worth value of tightening a typical 12.5-ft^2 window with 16 ft of crack from the ANSI standard to a tighter one, a change from 0.5 ft^3/min^2 ft of crack at 0.3 in H_2O to only 0.15 ft^3/min ft. The calculations, given below in the *Airtightness Economics* section, represent conditions at Ft. Wainwright and Ft. Richardson and the civilian sectors in Fairbanks and Anchorage.

RESULTS AND CONCLUSIONS

Moisture on windows

Each time we observed ice or moisture on a window we plotted dewpoint spread against indoor-outdoor ambient temperature spread on the thermal model in Figure 4. We thereby determined whether the model would have predicted moisture or ice for the prevailing conditions. Appendix C shows some sample comparisons.

Condensation or ice occurred more frequently than the model predicted for daytime conditions. Two of 13 observations of double pane windows revealed frost or condensation under circumstances for which the model would predict none. The observations represented about a 5% greater ΔT_{ID} than the corresponding ΔT_{IS}. Only one of 24 predictions for triple-pane windows failed; however, these windows were not susceptible to problems with moisture.

Icing prediction was not as reliable. In this case the model predicted 7 of 12 instances when ice occurred. The ΔT_{ID} for which we measured and observed icing was, on the average, 18% less than the level for ΔT_{IS} for which ice or frost would be expected. However, our observations usually took place during the day when the conditions that formed the ice no longer prevailed and the window surface was thawing.

Given the effects of warming daytime temperatures, sunshine and heat outlets, the window thermal model proved to be a sufficient guide for predicting condensation or frost problems on the indoor surface of windows as a function of the number of glazing layers.

Airtightness

The most frequently specified ANSI standard for airtightness in uninstalled windows for cold weather use is 0.5 ft^3/min leakage per foot of crack for a pressure difference across the window of 0.3 in. of water. However, the mean value of airtightness for all the windows, adjusted for how many of each we measured, was more than double this standard. Table 3 shows the mean airtightnesses of different types. One aluminum double slider achieved the best airtightness of the 23 windows sampled, 0.2 ft^3/min ft. New windows were, on the average, more than twice as tight as old.

Table 3 also shows that window airtightness with the frame included is about 1.4 ft^3/min ft. The joint between the window and its rough opening is one of the worst sources of air leakage. However, it is difficult to measure because the pressurized airflow may short-circuit along the wall back to the same

Table 3. Means of installed airtightness values (ft^3/min per ft of crack at 0.3 in. water). Number of samples of each window type in parentheses.

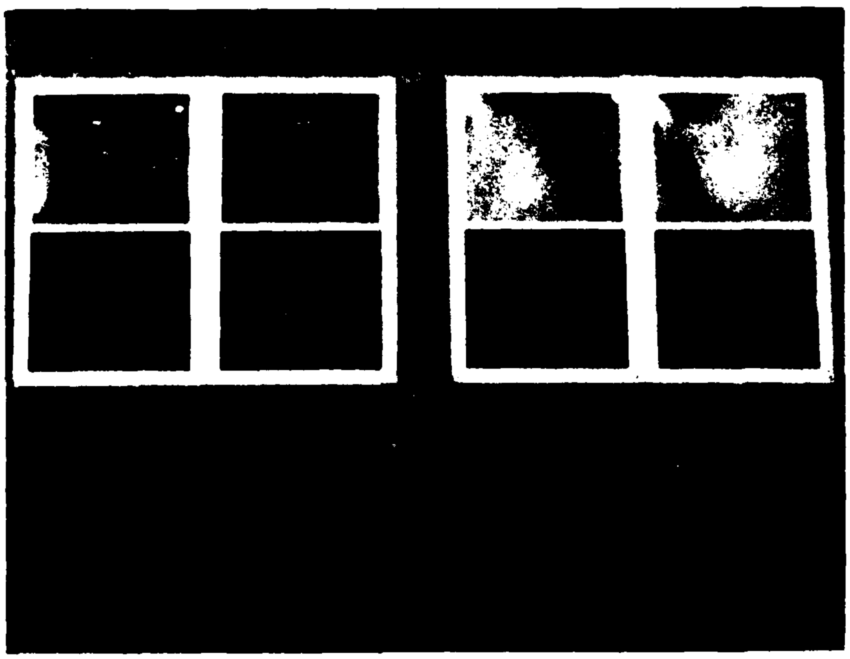
	Window in rough opening	*One sash layer wood prime*	*Two sash layers wood prime*	*Two sash layers aluminum*
New	1.4 (4)	0.95 (3)	1.7 (1)	0.55 (5)
Old	-	-	1.7 (6)	-

side as the pressurization device. For those particular windows, inclusion of the rough opening in select measurements more than doubled the air leakage per unit crack over that from the sash and frame along.

To determine the influence of proper installation, we measured the airtightness of new double-hung windows from the same manufacturer in two different installations. In one case the window was installed properly; in the other case the steel bands that hold the window's shape until it is shimmed into the rough opening were mistakenly cut prior to installation so that leakiness increased by about 30%.

Our limited sample revealed no evidence that cold weather affects window airtightness significantly.

Air leakage can be a significant factor causing condensation and frost to form. The cover of the report shows windows where the storm sashes are evidently tighter than the prime sashes (which may be partly open). Consequently moisture leaks through the inner layer, reaches the cold outer pane and frosts it up. This problem can occur even with new windows. Figure 7a shows windows with an exterior storm sash which consistently iced up in moderate cold as did hundreds of similar windows. Airtightness measurements showed one such window to be seven times leakier than the standard. The window in Figure 7b was consistently frost-free, even in extreme cold. Its storm sash was mounted on the prime sash on the



a. Window with leakage past storm sash.

Figure 7. Upstairs windows in similar locations and of equivalent quality; the windows (a) consistently frosted in moderate cold and windows (b) remained clear in extreme cold.

b. Window without significant leakage past storm sash.

Figure 7 (cont'd). Upstairs windows in similar locations and of equivalent quality; the windows (a) consistently frosted in moderate cold and windows (b) remained clear in extreme cold.

inside. Yet, with no air leakage past the storm sash, frosting was not a problem.

Airtightness economics

To calculate the annual cost of air leakage from windows, we had to make simplifying assumptions about the effects of wind and temperature. We assumed wind to be blowing constantly at its recorded mean speed for each month. To test the sensitivity of this variable, we used eq 7 to calculate air leakage with no wind and with double the mean wind as shown in Tables 4 and 5.

The monthly mean wind speed scenario offers significant incentive for improving window airtightness, as Table 4 demonstrates for a window in a single-story house. At a windless location in Anchorage (column 2), it would be worth up to $2.74 in extra first cost to tighten the window. With wind as significant as we assume in our base case, the figure is $11.18 and if wind is twice as strong in effect, the figure is $25.90.

If we substitute greater stack pressure, as found in a two-story building, the potential for savings is much greater in Fairbanks where temperatures are much lower than in Anchorage, as Table 5 demonstrates. The fact that installed performance shown in Table 3 is much worse than the factory-fresh standard greatly increases the incentive for improvement. Improvement from 1.5 to 0.15 ft^3/min ft is 3.9 times more significant than an improvement from 0.5 to 0.15 ft^3/min ft.

In many cases the physical improvement to the window results from merely ensuring continuity of the seal around a corner, adding a Mylar strip down the middle at a brush seal, changing from a double hung sash unit to a casement or possibly adding another latch to the casement. Several American manufacturers offer windows with the 0.15-ft^3/min ft performance at little additional cost over comparable conventional units. Certainly in Alaska the tighter standard is easy to justify.

Tightening windows offers significant conservation investment incentives compared with adding thermal resistance with triple glazing instead of double. Table 6 was calculated by multiplying the change in conductance between a two- and a three-pane window by the heating degree days and energy costs of each location shown; it indicates a $17 incentive for adding the third pane at Ft. Richardson. The comparison between Table 6 and Tables 4 and 5 favors reducing air leakage over installing triple panes, if we consider the nearly four-fold improvement that 0.15 ft^3/min ft

Table 4. One-story building: justifiable extra first cost of tightening a window with 16 ft of crack from a standard of 0.5 ft^3/min per ft at 0.3 in. of H_2O to 0.15 ft^3/min per ft for the 25-yr life of the window.

	Anchorage area		*Fairbanks area*	
Wind assumption	*Ft. Richardson*	*City*	*Ft. Wainwright*	*City*
No wind	\$2.28 (1979)	\$2.74	\$4.92 (1979)	\$18.31
At monthly mean	8.89 (1979)	11.18	10.57 (1979)	39.34
At double monthly mean	20.59 (1979)	25.90	21.48 (1979)	79.93

Table 5. Two-story building: justifiable extra first cost of tightening window with 16 ft of crack from a standard of 0.5 ft^3/min per ft at 0.3 in. of H_2O to 0.15 ft^3/min per ft for the 25-yr life of the window.

	Anchorage area		*Fairbanks area*	
Wind assumption	*Ft. Richardson*	*City*	*Ft. Wainwright*	*City*
No wind	\$5.31 (1979)	\$6.60	\$11.98 (1979)	\$44.56
At monthly mean	10.78 (1979)	13.56	15.59 (1979)	58.00
At double monthly mean	21.85 (1979)	27.49	25.93 (1979)	96.48

Table 6. Justifiable extra first cost for having three panes instead of two in a new window installation, based on fuel savings over the 25-yr life of the building.

Location	*(\$/ft²)*	*(\$/12.5 ft²)*
Ft. Richardson (1979)	1.34	17
Anchorage at \$0.19/100 ft^3 gas	1.69	21
Ft. Wainwright (1979)	2.55	32
Ft. Greely (1979)	4.76	60
Remote Post (1979)	16.15	203
Fairbanks at \$1.00/gal. oil	9.47	118

would represent compared with the actual 1.5 ft^3/min/ft performance of many windows as installed.

RECOMMENDATIONS FOR WINDOWS IN EXTREME COLD

Our recommendations deal with the energy efficiency of windows and with adequate window performance under the moisture stresses found in buildings during severe winter conditions.

Airtightness

Air leakage is not only a cause of moisture problems on windows, but also a source of energy loss. Our calculations, with a wide range of assumptions, indicate ample justification for tightening Alaskan windows considerably.

Current Corps of Engineers and ANSI standards require most windows to achieve less than 0.5 ft^3/min of air leakage per foot of crack for a pressure difference resulting from the equivalent of a 25-mph wind. Performance of less than 0.15 ft^3/min ft at that pressure is not only economically very attractive, but also has been surpassed at reasonable cost by several American window manufacturers. This 0.15 ft^3/min ft standard just qualifies for the most airtight category according to Norwegian standards (Beckett and Godfrey 1974).

Unfortunately, installation and use can degrade the factory-fresh airtightness of a window significantly. Our observations showed degradation by a factor of three to be common. Our economic calculations indicate that installed window tightness at a level of 0.15 ft^3/min in Alaska is well worth the necessary care in labor and inspection to obtain that performance. The best installation we saw was 0.2 ft^3/min ft, still short of this goal.

Because air leakage is such an important facet of energy consumption by windows and other building elements, we recommend developing design data that characterize air leakage in the same manner that heating degree-days characterize seasonal heat loss from conduction. Any standard index for air leakage loads will have to divorce itself from a particular building configuration. Furthermore, an understanding of the cost of each method for improving airtightness, both at the factory and on the job site, would permit better recommendations for an optimum level of effort.

Air leakage played a large role in frost formation on outside panes. We saw hundreds of windows of comparable quality from two reputable manufacturers in equivalent application installations. One design was consistently ice-free in extremely cold weather and the other was consistently iced-up on the outer storm sash in moderately cold weather (Fig. 7), because it allowed moist air to leak to the cold outer pane.

Multiple glazing

The most widely used means for reducing heat loss through windows has been multiple glazing. Life cycle cost (LCC) calculations suggest that triple glazing is preferable to double glazing in much of Alaska.

The investigation shows that triple glazing in residences and barracks is especially important for controlling condensation, frost and ice. The likelihood of curtains or shades in residences makes the necessity for triple glazing even stronger because these coverings lower the inside surface temperature of the window surface and make it more likely to reach the dew or frost point. The office work environments we monitored do not generate enough moisture to present a major condensation problem for either double- or triple-glazed windows with or without curtains.

We recommend that all glazing be on a single set of sashes. Too often occupants by-pass the thermal qualities of windows with multiple sets of sashes by leaving one set of sashes open (Fig. 1). Our airtightness studies indicate that single sash systems can perform as well as multiple ones. The frame and sash should be better insulated than the glazing to ensure that moisture problems do not first occur on the window structure.

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APPENDIX A: MOISTURE LEVELS AND AIRTIGHTNESS

The hygrothermograph data, in conjunction with corresponding outdoor temperature records, offer interesting insight into the airtightness of the buildings they represent. *Airtightness* is the quality represented by C in eq 2; it is distinct from *air leakage*. Figure A1 shows the regression lines at each location for the moisture data first presented in Figure 5. Although the scatter of data causes a poor correlation coefficient, it is clear in each case that ΔT_{ID} is a linear function of ΔT_{IO}. Plotting data from year to year with the same occupants in both an office and a residence resulted in the highly repeatable regression lines seen in Figure A2. The data itself exhibited substantial scatter about these lines. We hypothesize that the slopes of the regression lines from data in Figure A1 reflect the airtightness of the structure and that the intercepts reflect the net effect of moisture generation, wind, and forced ventilation on air leakage.

The tighter a building is, the less a change in outdoor temperature will affect air leakage by the stack effect. Therefore a tight building will have a low slope in Figure A3. A leaky building, with a high slope in Figure A3, will have dry indoor air when outdoor temperatures are cold because the stack effect will cause rapid exchanges of indoor air for outdoor.

The occupants of a building are likely to generate moisture at a fixed rate and use the doors with a fixed frequency. Likewise, the fan system, when present, is likely to run regularly, and possibly the wind may blow independently of outdoor temperature. Therefore, more moisture from humidifiers, showers and cooking will shift the lines in Figure A4 downward. Ventilating the building with drier outdoor air shifts the curves upward. Consequently, an airtight building may experience much air leakage from frequent opening of doors and running of ventilation fans.

The hygrothermograph may become a convenient tool for measuring airtightness and moisture load, with proper backup from other measurement techniques. At the same time it may present a suitable tool for measuring air leakage over long time periods.

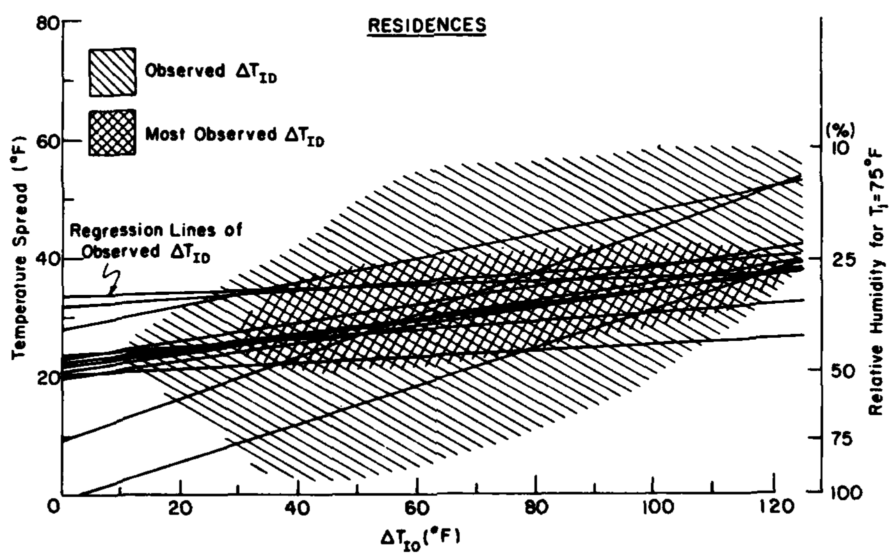
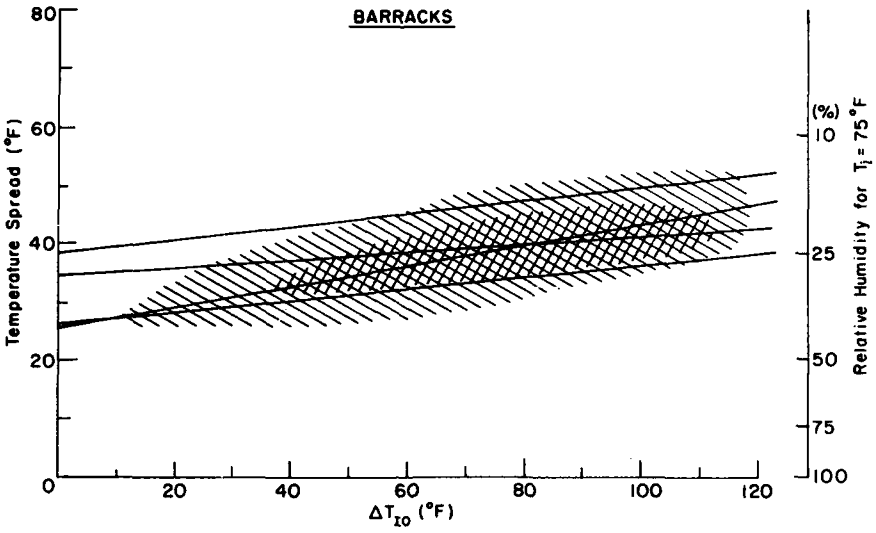


Figure A1. Observed moisture loads in buildings according to use. The lines are regressions on ΔT_{ID} vs ΔT_{IO} for each location monitored.



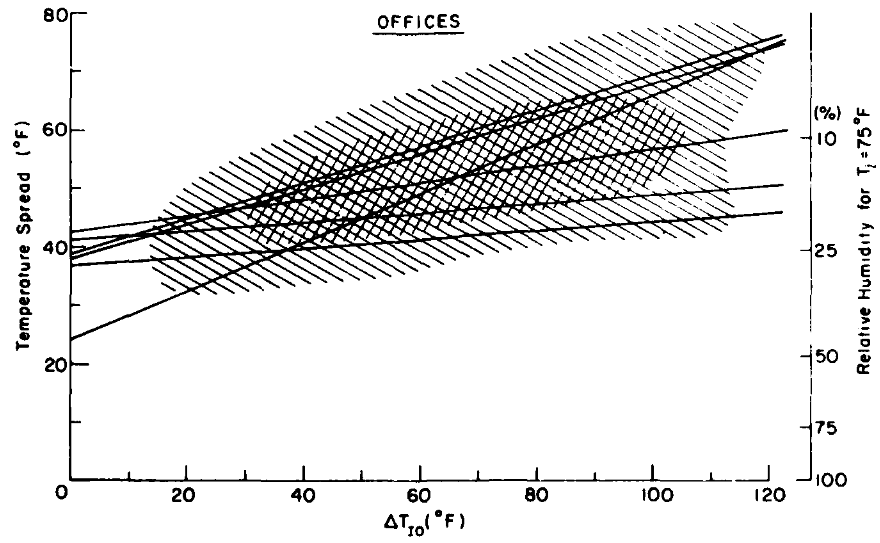


Figure A1 (Cont'd). Observed moisture loads in buildings according to use. The lines are regressions on ΔT_{ID} vs ΔT_{IO} for each location monitored.

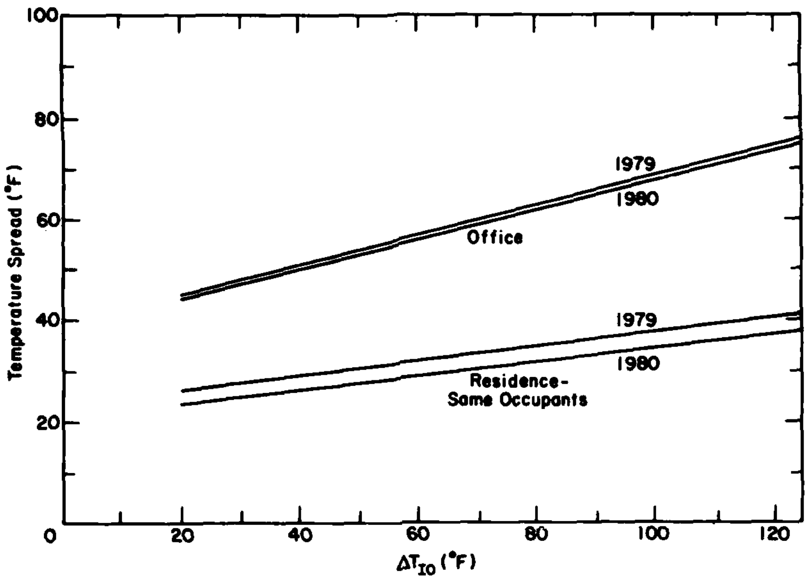


Figure A2. Regression line plots for recorded moisture loading (ΔT_{ID}) of an office and residence with the same occupants in two consecutive years. The repeatability of lines for each use is high.

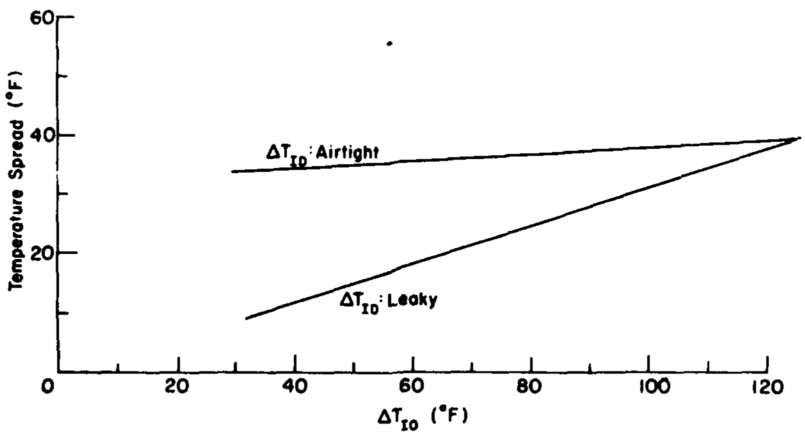


Figure A3. Regression lines for moisture loading in two similar residences. We conjecture that a steeper slope means a leakier building.

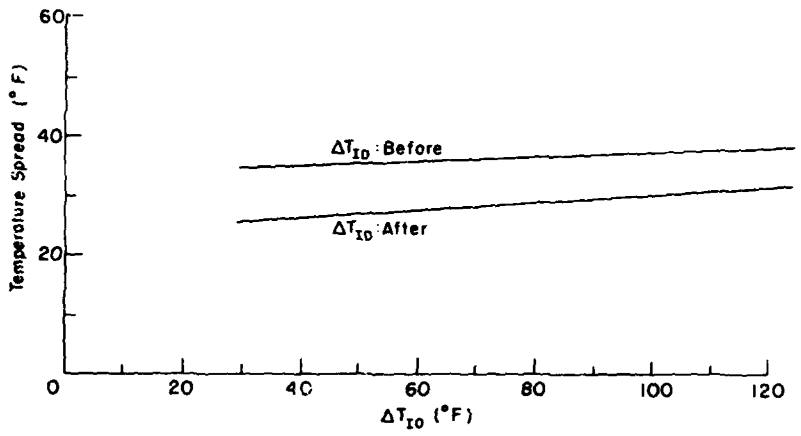


Figure A4. Regression lines of moisture loads in a residence before and after the installation of a larger humidifier.

APPENDIX B: DEWPOINT DATA

Figure B1 shows data obtained from the Eielson AFB and the Ft. Wainwright facilities engineering offices in the winters of 1979 and 1980, and from the CRREL Alaskan Projects Office (winter of 1980) and Corps of Engineers Office (winter of 1979).

The horizontal axis represents the spread between indoor and outdoor ambient temperatures. The vertical axis represents the spread between indoor ambient and dewpoint temperatures.

"Observed" and "most observed" are subjective terms which distinguish principal (or "mainstream") data from outliers. Since periods with low temperatures and a consequent high ΔT permit fewer observations at the right end of the graph, the "most observed" points are less frequent. However, such points are significant as extreme values for design.

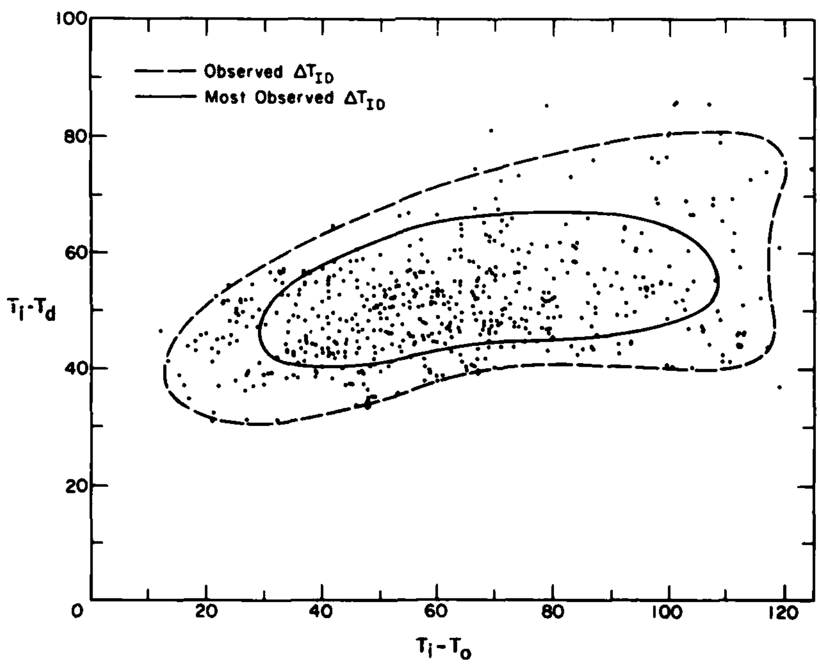


Figure B1. Data for the difference between indoor and dewpoint temperatures plotted as a function of the difference between indoor and outdoor temperatures for three offices at Ft. Wainwright and one at Eielson AFB.

APPENDIX C: SAMPLE OBSERVATIONS OF ICING

We compared the moisture, frost or ice conditions of windows with the model in Figure 4. We also noted the thermal parameters ΔT_{IO} and ΔT_{ID} from sling psychrometer and thermometer readings and used them to plot the condition of the window on the relevant portions of the model (number of panes, curtains). If the plotted points fell above the line, we expected no moisture problem.

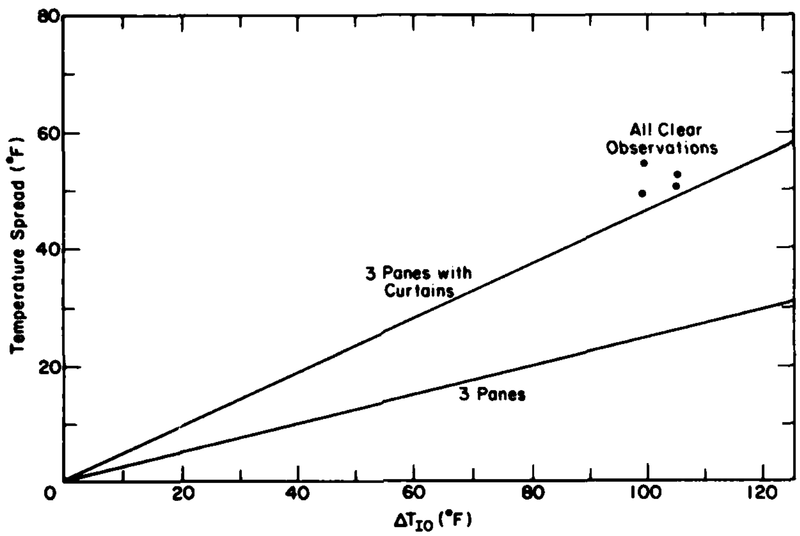


Figure C1. Observations of no ice or moisture on this wood, double-hung, triple-glazed window, which are consistent with the model expectation.

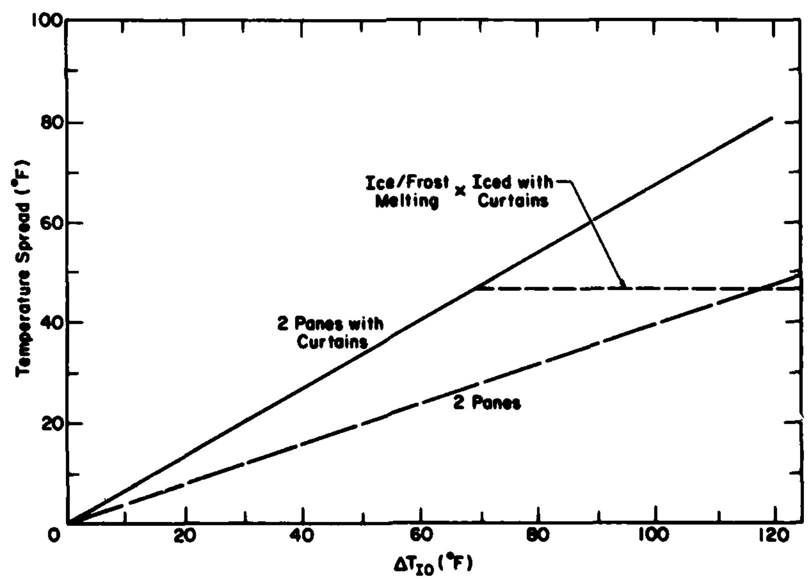


Figure C2. Prediction of ice on this aluminum, double-double hung (double glazed) window with curtains for a point below the line and above the freezing line.

A facsimile catalog card in Library of Congress MARC format is reproduced below.

Flanders, S.N.
Window performance in extreme cold / by S.N. Flanders, J.S. Buska and S.A. Barrett. Hanover, N.H.: U.S. Army Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1982.
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Bibliography: p. 14.
1. Air flow. 2. Alaska. 3. Cold regions. 4. Glass. 5. Humidity. 6. Life cycle costs. 7. Military facilities. 8. Thermal insulation. 9. Windows.

(cont'd) (see card 2)

Flanders, S.N. (Card 2)
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